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A sequential model for disaggregating near-surface soil moisture observations using multi-resolution thermal sensors

Olivier Merlin [a,*], Ahmad Al Bitar [a], Jeffrey P. Walker [b], Yann Kerr [a]

[a] Centre d'Etudes Spatiales de la Biosphère (CESBIO), Toulouse, France
[b] Civil and Environmental Engineering, The University of Melbourne, Australia

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ABSTRACT

A sequential model is developed to disaggregate microwave-derived soil moisture from 40 km to 4 km resolution using MODIS (Moderate Imaging Spectroradiometer) data and subsequently from 4 km to 500 m resolution using ASTER (Advanced Scanning Thermal Emission and Reflection Radiometer) data. The 1 km resolution airborne data collected during the three-week National Airborne Field Experiment 2006 (NAFE'06) are used to simulate the 40 km pixels, and a thermal-based disaggregation algorithm is applied using 1 km resolution MODIS and 100 m resolution ASTER data. The downscaled soil moisture data are subsequently evaluated using a combination of airborne and in situ soil moisture measurements. A key step in the procedure is to identify an optimal downscaling resolution in terms of disaggregation accuracy and sub-pixel soil moisture variability. Very consistent optimal downscaling resolutions are obtained for MODIS aboard Terra, MODIS aboard Aqua and ASTER, which are 4 to 5 times the thermal sensor resolution. The root mean square error between the 500 m resolution sequentially disaggregated and ground-measured soil moisture is 0.062 vol./vol. with a bias of −0.045 vol./vol. and values ranging from 0.08 to 0.40 vol./vol.

1. Introduction

Predicting the spatio-temporal variability of hydrological processes requires models that operate at different scales: evapotranspiration and infiltration at paddock-scale, run-off and drainage at catchment-scale, and atmospheric circulation at meso-scale. Due to the complexity of interacting processes (Chehbouni et al., 2008), the reliability of model predictions is intimately related to the ability to represent dominant processes in space and time using observations. Remote sensing has shown promise for this application due to its multi-resolution and multi-spectral capabilities (Choudhury, 1994).

Among the variables observable from space, soil moisture is one of the most crucial parameters that control hydrometeorological processes from paddock- to meso-scale. However, current and near-future space-borne soil moisture products have a spatial resolution of several tens of kilometers (Crow et al., 2005) —about ~40 km resolution for the forthcoming Soil Moisture and Ocean Salinity (SMOS, Kerr et al., 2001) mission—, which make their application to hydrological and agricultural models challenging.

Downscaling methodologies are therefore needed to improve the spatial resolution of passive microwave-derived soil moisture. To understand how soil moisture scales, the spatial structure of soil moisture fields has been statistically described using experimental data sets aggregated at a range of resolutions. Those studies (e.g. Rodriguez-Iturbe et al., 1995; Das & Mohanty, 2008) conducted over different sites and using either remotely sensed or ground-based data, conclude that soil moisture behaves as a fractal —i.e. follows a power law decay— over a wide range of scales. Moreover, there is a general agreement that the fractal behaviour of soil moisture is not simple over extended scale ranges, and changes in time (Kim & Barros, 2002b; Dubayah et al., 1997; Western et al., 2002). In particular, the recent study of Das and Mohanty (2008) suggests a transition from simple fractal (in wet fields) to multi-fractal (in dry fields) behaviour during a dry-down period. In practice, the multi-fractal framework seems an appropriate basis for downscaling soil moisture fields in areas where ancillary data (e.g. topography, soil properties, vegetation, rainfall) are available at high resolution (Kim & Barros, 2002a).

One drawback with statistical approaches is that they require a large amount of data given that their validity domain is generally limited to the conditions used for calibration. Consequently, there is a need to develop methods that use physical and observable parameters. Bindlish and Barros (2002) developed an interpolation method to downscale L-band passive microwave data using active microwave data at the same wavelength to improve the resolution of

* Corresponding author. Tel.: +33 5 61 55 85 08.
E-mail address: olivier.merlin@cesbio.cnes.fr (O. Merlin).

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brightness temperature fields prior to soil moisture retrieval. Similarly, Merlin et al. (2008a) developed a deterministic downscaling algorithm that combines 1 km resolution MODIS (MODerate resolution Imaging Spectroradiometer) data and a semi-empirical soil evaporative efficiency model. The main advantage of those approaches (Bindlish & Barros, 2002; Merlin et al., 2008a) over the purely empirical ones based on log–log plots (e.g. Kim & Barros, 2002a) is that some physical considerations are used to build a relationship between soil moisture and an ancillary observable; radar backscatter in Bindlish and Barros (2002) and soil evaporative efficiency in Merlin et al. (2008a).

In Merlin et al. (2008a), the disaggregation scale was fixed to 10 times the spatial resolution of MODIS thermal data to reduce the random uncertainties in disaggregated soil moisture. The authors observed that the sub-pixel variability of disaggregated soil moisture was significantly correlated with the observed fine-scale soil moisture variability, suggesting that the downscaling algorithm could be applied to spatial resolutions finer than 10 km. Nevertheless, that study did not apply the downscaling approach at multiple resolutions.

As a follow-up of Merlin et al. (2008a), this paper seeks to identify optimal downscaling resolutions in terms of disaggregation accuracy and sub-pixel spatial variability, and demonstrate the utility of this approach for sequential disaggregation of spaceborne surface soil moisture observations using multi-resolution thermal sensors. The development of a sequential approach is motivated by (i) the fact that high-resolution thermal data such as ASTER (Advanced Scanning Thermal Emission and Reflection Radiometer) data generally have a swath width smaller than the SMOS pixel and (ii) the hypothesis that the use of an intermediate resolution provides a better linearized approximation to a non linear function (e.g. soil evaporative efficiency model). One objective of the paper is to assess this hypothesis using data collected during the three-week National Airborne Field Experiment 2006 (NAFE'06). Airborne L-band data are used to simulate the 40 km resolution pixels expected from SMOS, and a thermal-based disaggregation algorithm is applied using MODIS and ASTER data. While the first part of the paper focuses on estimating optimal downscaling resolutions with MODIS and ASTER data, the second part takes advantage of these results to develop a sequential model for disaggregating ~40 km resolution microwave-derived soil moisture to 500 m.

2. Data

The NAFE'06 was conducted from 31 October to 20 November 2006 over a 40 km by 60 km area near Yanco (−35°N; 146°E) in southeastern Australia. While a full description of the data set is given in Merlin et al. (2008b), a brief overview of the most pertinent details are provided here. The data used in this study are comprised of wind speed measurements, L-band derived soil moisture and MODIS data collected over the Yanco area on twelve days, and ground measurements of 0–5 cm soil moisture and ASTER data collected over three 9 km^2 areas included in the Yanco area on one day (16 November) of the experiment.

2.1. Wind speed

Wind speed was monitored at 2 m by a meteorological station (located in the southwestern corner of the Yanco area, see Fig. 1 of Merlin et al. (2008b)) continuously during NAFE'06 with a time step of 20 min. The time series is illustrated in Fig. 1 of Merlin et al. (2008a).

2.2. Ground soil moisture

In situ measurements of 0–5 cm soil moisture were made using HDAS (Hydraprobe Data Acquisition System) on 16 November over three 9 km^2 sampling areas (denoted as Y2, Y9 and Y12) included in the 40 km by 60 km Yanco area (Merlin et al., 2008b). Within each 9 km^2 sampling area, an average of three successive measurements was made ~1 m apart at each node of a 250 m resolution grid.

2.3. PLMR-derived soil moisture

The near-surface soil moisture was retrieved from the 1 km resolution brightness temperature collected by the Polarimetric L-band Multibeam Radiometer (PLMR) on eleven days over the 40 km by 60 km area: 31 October, 2, 3, 4, 5, 7, 9, 13, 14, 16, 18 November (Merlin et al., in press). The surface temperature data used for the PLMR soil moisture inversion came from MODIS data on clear sky days, and from in situ measurements on overcast days. The root mean square difference between PLMR-derived and ground-measured soil moisture at 1 km resolution was estimated to 0.03 vol./vol. in non-irrigated areas. A bias of about −0.09 vol./vol. was obtained over pixels including some irrigation. This bias was explained by a difference in sensing depth between the L-band radiometer (~0–3 cm) and in situ measurements (0–5.7 cm), associated with a strong vertical gradient in the top 0–6 cm of the soil. Moreover on 3 November, which followed a rainfall event, the PLMR-derived soil moisture seemed to be affected by the presence of water intercepted by vegetation (Merlin et al., 2008b,a). In this study, data from this date were discarded.

2.4. MODIS data

The MODIS data used in this paper are the Version 5 MODIS/Terra (10:30 am) and MODIS/Aqua (1:30 pm) 1 km resolution daily surface temperature, and MODIS/Terra 250 m resolution 16-day Normalized Difference Vegetation Index (NDVI). The 16-day NDVI product was cloud free. In between the first (31 October) and last day (18 November) of 1 km resolution PLMR flights over the Yanco area, sixteen MODIS Version 5 surface temperature images with 0% cloud cover were acquired including nine aboard Terra (3, 5, 7, 8, 9, 10, 11, 17, 18 November) and seven aboard Aqua (31 October, 3, 4, 6, 8, 9, 17 November). Note that more cloud free images were obtained than from Version 4 surface temperature (Merlin et al., 2008a). The overestimation of cloud cover in Version 4 products and the subsequent increase of coverage in Version 5 land surface temperature products are discussed in Wan (2008). MODIS data were re-sampled on the same 1 km resolution grid as PLMR-derived soil moisture, and MODIS surface temperature was shifted of (+1 km E; −0.5 km N) and (+2 km E; 0 N) for Terra and Aqua respectively to maximize the spatial correlation with 1 km resolution MODIS NDVI, which was used as a reference for the co-registration.

2.5. ASTER data

The ASTER/Terra overpass of the NAFE'06 site was on 16 November 2006 at 10:30 am. Radiometric surface temperature was estimated from 90 m resolution L1B thermal radiances using the emissivity normalization method developed by Gillespie (1985) and Realmuto (1990) and implemented in ENVI (ENvironment for Visualizing Images, http://www.ittvis.com/envi/) image processing software. Temperature was computed for each of the five thermal channels using a uniform emissivity set to 1, and the actual radiometric temperature was assumed to be equal to the highest computed temperature. Pre-processing of ASTER-derived radiometric temperature consisted of (i) registering the image with an accuracy better than 90 m from reference points (ii) extracting data over three 12 km by 12 km areas centered over the three 9 km^2 sampling areas, (iii) removing data that were visually identified as cloud or as cloud shade on the ground (note that the scene was cloud free over the three 9 km^2 sampling areas Y2, Y9 and Y12) and (iv) re-sampling data at 100 m resolution. An important point is that ASTER-derived radiometric surface temperature was not corrected for atmospheric effects.